

Global Coasts: A Baroque Embarrassment of Riches

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Abstract: Coasts form the universal stage on which people interact with the global ocean. Our history is inextricably intertwined with the seashore, being a rich tapestry of archaeological sites that paint a vivid picture of people hunting, foraging, fishing and scavenging at the edge of the sea. Seascapes inspire diverse art forms celebrated through the ages. The world's sandy beaches have a flummoxing duality of anthropocentric purpose—ranging from the horrors when being theatres of war to first love under a rising moon. ‘Man’s Love of the Sea’ continues to draw people towards the shore: the narrow coastal strip contains everything from holiday cottages to megacities. This coastal concentration of the human population is problematic when shorelines erode and move inland, a geological process fastened by climate change. Society’s response is often a heavy investment in coastal engineering to complement and enhance the natural storm protection capacity of beaches and dunes. The coast’s immense cultural, social, and economic significance are complemented by a wealth of natural riches. In the public’s eye, these ecological values can pale somewhat compared with more imminent ecosystem services, particularly protecting human properties from storm impacts. To re-balance the picture, here we illustrate how peer-reviewed science can be translated into ‘cool beach facts’, aimed at creating a broader environmental appreciation of ocean shores. The colourful kaleidoscope of coastal values faces a veritable array of anthropogenic stressors, from coastal armouring to environmental harm caused by off-road vehicles. Whilst these threats are not necessarily unique to coastal ecosystems, rarely do the winds of global change blow stiffer than at the edge of the sea, where millions of people have created their fragile homes on shifting sands now being increasingly eroded by rising seas. Natural shorelines accommodate such changing sea levels by moving landwards, a poignant and powerful reminder that protecting the remaining natural land is *primus inter pares* in coastal management. There is no doubt that coastal ecosystems and coastal communities face august trials to maintain essential ecosystem services in the face of global change. Whilst bureaucracies are not always well equipped to counteract environmental harm effectively, using measures carrying a social license, many communities and individuals have encouragingly deep values connected to living coastlines. Building on these values, and harnessing the fierce protective spirits of people, are pivotal to shaping fresh models that can enhance and re-build resilience for shores that will continue to be a ‘baroque embarrassment of coastal riches’.

Keywords: coastal management; environmental values; sandy shores; ocean beaches; conservation



Citation: Schlacher, T.A.; Maslo, B.; de Schipper, M.A. Global Coasts: A Baroque Embarrassment of Riches. *Coasts* **2022**, *2*, 278–301. <https://doi.org/10.3390/coasts2040014>

Academic Editor: Javier Benavente González

Received: 22 April 2022

Accepted: 24 October 2022

Published: 8 November 2022

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1. Humans at the Edge of the Sea: The Coastal Connection

‘A striking characteristic of most coastal barriers in their natural state is their tendency to migrate or recede gradually landward. That being so, it hardly seems sensible that people build houses on shifting sands. Perhaps that can be explained by man’s romantic love of the sea.’ [1]

1.1. Vulnerable Coastal Cities Arising from ‘Man’s Love of the Sea’

It is devilishly difficult, and rather dangerous, to explain decisions and actions powered by romantic love. Humanity would be robbed of many a fantastic artistic work were it not a beguiling, yet often impossible, task to do so (Figure 1). Cities built on the malleable sands that naturally form often fragile dunes on ocean-exposed beaches so flummoxing and illogical that ‘man’s romantic love of the sea’ must surely be considered seriously as the *raison d’être* for our lemming-like rush to the coast [2].



Figure 1. Bandits on a Rocky Coast (Salvator Rosa, 1655–1660). (Image Source: The Metropolitan Museum of Art (‘The Met’), New York. The image of OA—Open Access. As part of the Met’s Open Access policy, the image can be freely copied, modified and distributed, even for commercial purposes. <https://www.metmuseum.org/about-the-met/policies-and-documents/open-access>; accessed 26 October 2022) Note: Coastal landscapes have inspired artist throughout the ages, their sense of drama continuing unabated. Here, the jagged rocks frame a semi-hidden cove (presumably a smuggler’s cove) creating the seascape-stage for bandits arguing on the rocky shore. Few characters can dramatically outshine bandits and coastal smugglers, enduring symbols of romantic escapisms and defiance against the reach of government.

This rush has created a string of cities at the edge of ocean-exposed beaches, housing the human lemmings on a migration towards the seashore that is unprecedented in human history [3]. The narrow coastal strip is predicted to experience continual mass movement, population growth and urbanisation in the future [4,5]. Among coastal landform types, sandy beaches are prime sites for settlement, tourism and recreation [6]. Ocean-exposed, wave-dominated, sandy beaches and coastal dunes are, however, complex and pliable systems, their width and shoreline position being continuously moved by storms, variations in sea level, and changes in sediment supply and transport [7]. Considering the enormous investments in housing and infrastructure built on shifting sands, it is not surprising that shoreline recession and beach erosion are the dominant themes in coastal hazard management [8–12]. Shoreline retreat becomes particularly poignant for ocean beaches

subjected to coastal squeeze [13], being trapped between human structures on the landward side and rising seas caused by climate change [9].

1.2. Coasts as Ever-Changing and Malleable Seascapes

Forming the edge of the land that is the final frontier for the enormous energy of the ocean, coastal landscapes are very rarely static. That change is the overriding attribute of many coastlines has been recognised for Millennia, poignantly illustrated by King Canute's demonstration of secular power having no control over the tides. In somewhat less apocryphal ways, the twisted geological history of coastal seascapes has been richly documented for at least two centuries. Charles Lyell's (1797–1875) towering contribution to geology illustrates this well, emphasising 'deep time' as the key to understanding earth's history. In the face of humanity's rush to the sea, and our fear of how to defend against the rising seas, it seems incredulous to observe the cavalier attitude of real estate businesses that wilfully ignore coastal instability, notwithstanding that we have known for centuries that coastlines rarely stay still [1].

Undeniable evidence of marked changes in the position of the shoreline on sedimentary coasts is preserved in the geological structures of coastal seascapes [14]. On sandy shores, the stratigraphic record often demonstrates that sea level variation is the master factor controlling the formation, persistence, shape, resilience, and longevity of beaches, most notably the position of the coastline [15]. It also shows that beaches migrate landwards ('shoreline retreat') under rising seas [16] when there is no human infrastructure arresting this movement [17]. Tectonic events can result in remarkable changes to coastline topography [18], and mega-storms re-shape the coastal seascape, resulting in horrendous damage to coastal assets and tragic loss of human lives [19].

Coasts have been changing for millennia, but humans have become the major agent of geomorphic change only during the past few centuries. Furthermore, the spatial reach of anthropogenic impacts on coastlines has massively expanded to operate now at a truly global scale. The large numbers of coastal armouring structures (e.g., seawalls, groynes, breakwaters) are testimony to our massive investments aimed at 'holding the line' at the edge of the sea [20]. How humans shape seascapes can be a highly complex interplay between local practices, physical forces, socio-cultural norms, and geo-political events. In this context, Belknap and Sandweiss [21] provide a fascinating account of the intersection between societal destruction caused by colonising forces and the loss of key human practices that shaped coastal landforms. In Peru, the harvesting and processing of beach clams created sheets of discarded midden shells. These shell deposits played an important role in preserving dune ridges from erosion and deflation: indigenous maritime people effectively provided the mechanism for maintaining steep sandy beach ridges armoured by shell middens. The rapacious Spanish conquest resulted in a cataclysmic loss of indigenous culture; it also fundamentally changed coastal morphology by destroying the socio-economic structures that underpinned clam harvesting and the creation and maintenance of shell middens. It is a fascinating story of geopolitical events destroying the human fabric that for millennia maintained a dynamic coastal landscape [21]. Interestingly, shells continue to be used to stabilise shorelines, in settings as diverse as coastal villages in Timor Leste and large-scale investments to create 'living shorelines' in the US [22].

1.3. Coasts Connect People with the Ocean and with Ocean Life

A minute percentage of the global population will ever feel the teak decking under their feet whilst yachting nonchalantly offshore. More will engage in fishing or ply the seven seas on commercial ships. For the populace sans yachts or other sea legs, the connection to the ocean is limited to the seashore. Thus, coasts connect people to the global ocean and other people on far-flung shores. Humans inhabit and use coasts in a bewildering variety of ways, from playing boccia during the annual holidays to harvesting seafood as an essential livelihood. In fact, few connections to the sea are as old, widespread and important as fishing and the harvesting of sea creatures from the shore. 'Foraging' on the seashore not

only provides vital nutrition for artisanal fishers and coastal communities, but it has seen a renaissance connecting city dwellers to nature [23]. In fact, people's fascination with the seashore has for a long time found an expression in 'beachcombing'. People forage amongst flotsam and jetsam to find treasures, discover objects of curiosity, and spot beached debris that floated on the seven seas [24]. It appears that foreign human-made objects have been recovered from beaches by Indigenous people for quite some time, connecting cultures across ocean basins in unexpected ways. For example, the First Nation People of Labrador and north-eastern Greenland were familiar with iron, in the form of nails, many years before direct contact with Europeans; the likely source of such iron was driftwood, possibly having drifted across the Atlantic from European shores [25].

Some of the connections that beaches form between the ocean and the land are distressing or seem unsavoury to all but a hardy biologist. Marine animals beach on ocean shores, either accidentally stranding alive or as wave-cast dead carcasses washing ashore after drifting at sea [26]. Nobody who had the dubious pleasure of experiencing the ripe aromas of spoiled whale meat will argue that research on stranded carcasses can be challenging to the senses (and socially isolating). However, the olfactory signals belie the biological insights that 'smelly science' can deliver [27]. An astonishing diversity of iconic vertebrate scavengers feeds on animal carcasses stranded on beaches [28,29]. Amongst the many facets and that 'stranding science' can encompass some include: (a) species discoveries some rare marine animals are almost exclusively known from stranded individuals; (b) distribution and population structure of marine mammals (inc. gestation lengths, breeding seasonality, growth rates); (c) 'functional discoveries' in physiology and anatomy (e.g., a remarkable heat exchange system was discovered by dissecting beached dolphins, seals, and manatees; they can regulate their body heat at levels high enough to function adequately in a cold ocean, but at levels low enough to preserve fragile sperm and developing foetuses); (d) tracking the toll of diseases, toxicants, shipping, and floating marine rubbish (e.g., ghost fishing gear); (e) tissue samples analysed for DNA composition can reveal levels of population mixing and 'family trees' for regional populations, and stable isotope values can give us a time-integrated picture about the distinct classes of food items animals consumed in the preceding weeks to months; (f) nursing injured animals to rehabilitate victims of boat strikes and gunshot wounds back into the wild; and (g) satellite-tagged seals, turtles, and whales that have been successfully re-floated broadcast 'live pictures' about their movements, behaviours and habitat choices [26].

1.4. Wildlife on Coasts: 'Nature Red in Tooth and Claw'

Coastal seascapes have inspired artists for Millenia, creating some of our most treasured works. Coasts can, however, be raw places of unspeakable tragedy [30], illustrating Alfred Lord Tennyson's sentiment of 'Nature Red in Tooth and Claw' at its most cruel. In sharp contrast to the serene scenes painting motley fisherfolks and glowing sunsets, there exist other truths, such as sharks attacking people in the surf zones of ocean beaches [31]. Every person that dies is a profound and fundamentally tragic loss. This loss is always the ethical imperative and consequently, there can be no debating the trauma experienced by shark victims and their families.

In the spirit of open intellectual enquiry, one may, however, try to examine human-shark interactions through the prism of three complementary contexts: (i) a human safety perspective, (ii) our free-willed choices, and (iii) the role of sharks in marine food chains: First, The risk of dying from cardiovascular diseases caused by the fatty fish and chips consumed whilst overlooking a 'sharky' beach is orders of magnitude higher than actually passing those greasy kilojoules up the nearshore food chain via a shark. Secondly, the only mammals that have evolutionary reversed their tracks back into the sea are whales, seals and their blubbery chums. By contrast, humans have remained firmly terrestrial mammals and enter the surf voluntarily to seek pleasure and excitement. Most activities that amuse us carry some risks. Swimming or board-riding in the surf is not risk-free; the possibility of a shark encounter is always present: exposure to this risk is voluntary. Thirdly, unknown to

most beach visitors, the surf zones of ocean shores harbour a great diversity of fish species, spanning a spectrum of sizes, feeding modes, and positions on the trophic ladder; sharks are the apex consumers in these food chains [32–35]. These perspectives may, arguably, be seen as controversial. Still, all facets of how humans interact with coastal habitats and animals should generally be examined from multiple angles as long as this does not cause preventable human anguish.

2. Coasts as Windows to Our Past

By the time Geoffrey Chaucer’s motley band of medieval pilgrims from the Canterbury Tales reached the shrine of Thomas Becket, the great cathedral’s colourful windows firmly caught their gaze, fuelling their imaginations, religious or otherwise. The dazzling cathedral windows’ effect is undiminished today: it is a riotous kaleidoscope of colours, shapes, symbols, beasts, mythologies, and human foibles their colourful diversity giving us different mental prisms to view the world around us. Archaeological sites along coasts are metaphorically our cathedral windows to the past: they tell stories of ancient civilisations and cultures, catastrophic environmental events, catches of seafood, cultivation of new crops, foraging and scavenging along the shoreline, hunting of ferocious beasts and feasting on them, religious practices, births and burials, tools and ornaments, and much more coasts hold outstanding records of our shared human history and the environment that supported our cultural evolution.

2.1. Coastal Societies and Cultures at the Edge of a Violent Sea

Archaeological deposits in the coastal zone are invaluable archives of the story of First Peoples, told by burial sites, middens, meeting places, local stone quarries, fish traps, intensive net fishing, fields of crops, buildings, irrigation systems, temples, and diverse artefacts. It is increasingly being recognised that First National lived in complex coastal societies and interacted with their maritime environments in sophisticated ways [21,36]. However, it is also becoming evident that massive environmental disasters can abruptly decimate coastal societies. For example, between ≈ 5800 and 3600 cal B.P., large settlements in coastal Peru contained impressive architectural monuments and diverse ways of supporting their populations (e.g., intensive net fishing, irrigated orchards, fields of cotton) [37]. These civilisations’ demise (≈ 3800 B.P.) has been linked to a series of natural disasters earthquakes, El Niño flooding, beach ridge formation, and sand-dune incursion—that irrevocably changed their natural support systems [37].

Sedimentary coastlines are continually adjusting their position in response to a range of physical forces operating at a range of scales, from Millenia (e.g., eustatic sea-level adjustments), centuries (extreme storms), years to decades (sea-level rise linked to climate change) and weeks to days (storms) [38]. In the context of hazards posed to coastal societies by meteorological and oceanographic drivers, it is the study of ‘mega storms’ that reveals the tenuous existence of humans at the edge of the sea. The 2004 Indian Ocean tsunami created wave heights reaching 35 m. It is a particularly poignant example of extreme environmental forcing. Histories of coastal societies did not include stories of such massive Tsunami events, which appeared ‘unprecedented’ for the region. However, sand sheets deposited on the coastal plain by past Tsunamis provide a record of events going back over 1000s of years, revealing massive storms around AD 1290–1400 and AD 780–990. This palaeotsunami record suggests that such events occur infrequently enough for entire human lifetimes to elapse between them [39], challenging our capacity to properly assess coastal hazards that have return periods longer than our histories [38].

2.2. Shelled Seafood Is a Prime Source of Nutrition That Creates Rich Historical Records

Caves in sea cliffs and sedimentary deposits in coastal dunes provide us with a tightly woven tapestry of archaeological diets. The remains of animals and humans allow us to make plausible inferences about the diet and foraging modes of early humans and ancient civilisations [40]. Seashores support diverse assemblages of invertebrates, especially

molluscs (snails, clams, oysters, mussels) [41,42]. Molluscs can typically be easily collected by prying them off rocks or digging them out of the sand. Molluscs can also be highly abundant, such as wedge clams on ocean shores, and they are an excellent source of protein [43,44]. Therefore, it is not surprising that the diet of humans living on the coast generally contains copious molluscs. In fact, some of the most impressive archaeological deposits are mounds of mollusc shells; these ‘shell middens’ occur in diverse topographical and geographical settings [45]. Because coastal people collected a great diversity of mollusc species, the species composition of the remains provides a fascinating opportunity to track ecological change through time [46].

2.3. ‘Blood on the Sand’: Humans as Coastal Scavengers and Hunters

Humans have occupied coastlines and foraged along the seashore for hundreds of thousands of years [40]. Ocean beaches are typically depositional environments, making them natural stranding sites for marine animals that perish at sea, such as seals, dolphins, seabirds, and fish. These stranded animal carcasses provide a source of nutrition that is easily accessible on sedimentary shorelines. In sharp contrast to hunting wild beasts, scavenging also carries negligible risks. Access to animal tissues of high nutritional value, coupled with the much lower risk of hunting-related injury, suggests that First Peoples have used shoreline scavenging as a viable means of resource acquisition [40].

Scavenging is a highly plausible mode of foraging along coastlines, and the story of scavenging comes with two tantalising twists. First, where feasible, actively hunting for marine vertebrates would have most certainly complemented scavenging for dead animals. The long-standing debate about the relative contribution of scavenging versus hunting to the diet of humans illustrates that reconstructing the exact modes of resource acquisition can be challenging. Still, purposeful kills of seabirds and seals, even using small watercraft to reach nearshore islands, were likely employed by First Peoples [40,47]. Secondly, humans may have ‘outcompeted’ other species of vertebrate scavengers patrolling the seashore in search of carcasses. This inference stems from an intriguing collection of animal remains deposited by Neanderthals in the caves of Gibraltar [48]. The deposits contain the expected remains of herbivores (e.g., red deers, ibex and boar), marine mammals (seals, dolphins) and molluscs, all of which can be expected to form part of hunters and scavengers on the Iberian peninsula. What is astonishing, though, are the fossils of carnivore species that are known to include scavenging on ocean beaches as part of their foraging repertoire: grey wolves, hyenas, leopards, and brown bears [48,49]. The presence of carnivore fossils raises the questions of their mode of death and origin, with at least two hypotheses: (1) The predators entered the cave to feed on the spoils of the Neanderthal’s bounty; or (2) The Neanderthals hunted (killed) the carnivores whilst the animals consumed carcasses along the shoreline. The first hypothesis (‘uninvited cave buffet visitors’) lacks a compelling explanation of how several fierce predators died on the spot. The alternative hypothesis (‘humans outcompete carnivores at animal carcasses’) suggests adaptive flexibility in the mode of food acquisition, switching between scavenging and hunting as opportunities arose. From the perspective of hyenas, leopards and bears, it posits that the animal scavengers became the hunted, killed in ambushes set by our ancestors around beached carcasses. There is blood on the sand, a thriller written by the quill of man’s ancient foraging histories.

3. A Potpourri of Ten ‘Cool’ Beach Facts

The fantastic tapestry of natural riches that coasts weave is impossible to describe in a way that reflects that the true colour and breadth of geological, oceanographic and ecological features at the edge of the sea. In the public’s eye, ecosystem services provided by coasts often take primacy, particularly the role of coastal landforms to protect human properties from storms. By contrast, other environmental values of coasts are not always appreciated. As a small gesture to re-balance this picture, here we illustrate how values can be ‘showcased’ in the form of ten ‘cool beach facts’: these are, of course, not a fully representative cross-section of coastal structures and processes, but rather a potpourri

(in no topological order) of vignettes that tell fascinating stories—canapes of coastal science to pique interest and awaken an appetite to explore more fascinating coastal cuisine.

(1.) *Beach Landscapes: Ridges, Runnels, Scallops, Ripples, Bars and Pyramids!*

Who does not love building a sandcastle? It is a joy because we can easily form the sand into many wondrous shapes. Ocean waves, tides, and currents do the same, shaping beach sands into landscapes at the edge of the land. At a fleeting glance, beaches may appear flat and featureless. At a closer look (and a bit of rambling down the shore), beaches reveal a cornucopia of structures: ridges, runnels, ripples, bars, banks, and even natural pyramids formed from shingles. The beaches between the low- and high-water line are also part of a bigger system that includes the dunes backing them and the surf-zone fronting them: all are creatures of sand, and all are continually re-shaped by natural forces into sandy landforms of all types and sizes. There is no such thing as a simple beach landscape [50–54]. Rambling through the coastal countryside is a walk in the park to make new discoveries.

(2.) *The Vanity of the Sands: Every Single Sand Grain Has a Story.*

Whilst the grains forming beaches (aka ‘sand’) can have multiple parents, most modern mixed families openly embrace geological break-ups (i.e., the weathering of once proud rocks and mountains into smaller fragments) and invite dead bodies (i.e., biological origins being the skeletal remains of organisms). No matter what the exact paternity may be, sand grains have a story: their surface pitting and fissures are witnesses of forces crushing them, rolling them, burying them, blowing them, bouncing them, unearthing them, freezing them, baking them in the sun, all the while remaining the fundamental building blocks of dunes and beaches [55]. By way of analogy, think of the weather-beaten faces of people who have worked the land and plied the seven seas—their images tell of rich and moving stories, each unique and valuable. Sand grains are lousy at hiding things—their stories are written all over their stone-cold faces.

(3.) *Oxygen Factories in the Sands: Minute Plant Life Blooms on Beaches.*

Only the driest, hottest or coldest beach sands are pure rock material without life. Most beach sands are a mixture of the actual non-living grains (i.e., weathered rocks and the fragments of animal/protozoan skeletons) and minute plant and animal life. Some of these organisms are smaller than sand grains, attaching themselves to their surfaces. Others live in the spaces among sand grains, and their abundance can reach millions per square metre of beach [56–58]. Tiny algae can be spotted with the naked eye when sands turn golden or green in colour: this colour change is caused by countless algae living within the sands (i.e., one can find 20,000 individuals per cubic centimetre of beach sand) [59–61]. These algae are not lame ducks: they can actively move, migrating up and down through the sand. When concentrated near the surface, they can turn beach sands into shades of green and yellow. Being plants, they use sunlight as the energy source to produce new biological matter; a ‘by-product’ of manufacturing this new organic material is oxygen—the elixir of life [59–61]. Do not throw stones in coastal glasshouses: Beaches are amazing greenhouses full of living and breathing organisms.

(4.) *Worms and Other Cool Creatures Lurk in Beach Sands.*

Digging for worms in backyards, compost heaps, and on the seashore is the first step of many a memorable fishing trip. Most worms meet an untimely death, their last defiant act being a wriggly morsel of fish food on a hook. Worms are typically a few centimetres long, and rarely do they grow much thicker than a finger. Now meet ‘*Balanoglossus gigas*’, a worm burrowing in the balmy sands of the Brazilian Coast. It is a perfectly harmless creature, but as far as worms go, it is a giant of a beast: 1.5 m long [62]. Whilst spectacular in size, it is but one example of the fantastic animal life that beach sands hold. The commonly held belief that sandy beaches are mostly lifeless piles of sand is a complete fib: beach sands teem with life. One simply has to look a little harder, mostly under the surface of the sand and at night. All invertebrate animals living on ocean beaches either dig down into

the sand or hide under stranded algae, logs, and other flotsam and jetsam. Beach animals burrow and hide to avoid being eaten by birds (everyone has experienced seagulls on the beach, including their metabolic actions) or being washed out to sea by waves. Crawling and skipping around at night is also much safer. A spectacular diversity of fantastic animals lies just below the surface of the sands [11,63]. Warning: digging below the beach surface gives you worms and crabs.

(5.) *Beach Life Amongst the Touchy Kiwis.*

New Zealand's flightless Kiwi bird is one of the most remarkable products of avian evolution. The adorable and 'very huggable' Kiwis hunt for food by probing their long bills into soft earth and sand. Their eyesight is embarrassing. Kiwis make up for poor eyesight with remarkably acute senses of smell and touch. Having to rely on senses other than vision to detect prey, Kiwis even have developed a sense called 'remote touch': they can detect vibration and pressure cues from prey within the substrate, using a unique organ at the tip of their bill. Where natural forests back the seashore, Kiwis come down to beaches at night to forage for tasty invertebrate morsels along the shoreline. The sight of Kiwis foraging on a seashore is a captivating symbol of evolution at its creatively finest, most peculiar, and downright loveable. Kiwis searching for prey also remind us that animals are abundant (at night) and diverse on sandy beaches (e.g., sand hoppers, sandflies, beetles, slater, worms, snails, crabs, etc.). This bonanza of animal life supports not only the peculiar Kiwi (in a peculiar country), but a myriad of other birds foraging on the sands of the planet's sandy beaches [64,65]. There is so much more to Kiwis than rugby.

(6.) *'Like a Rolling Stone': Sand Grains on The Move.*

Perhaps the most outstanding attribute of coastlines made from sand is their continuously changing shape, width, height, and position: Sandy shores are rarely stable. The ability to change shape requires sand to have one fundamental property: it must be able to move. The physical energy for sand to move on sedimentary shorelines is provided by various agents: wind, currents, tides, waves, humans, etc. Geologists have studied coastal sand movement for well over a century. It remains a vital profession, especially on retreating shorelines where ocean waves threaten humans and their assets. What is rarely appreciated is the vocabulary that the humble sand grain has acquired: (i) a grain *rolling* along the surface under the force of the wind, 'creeps'; (ii) when a grain collides with another grain and the crash lifts one grain into the air, it now moves by 'saltation', or 'jumping'; (iii) when the wind blows strong enough, and long enough, the lifted and wind-blown grain cannot drop to the ground—it now moves 'suspended' [66,67]. Those beach sand grains are the original 'rolling stones'.

(7.) *Crabs That Breathe Air with their Legs.*

A group of crabs found on sandy beaches, called the 'sand bubblebers' (species of the genera *Scopimera* and *Dotilla*), have moved a very long way from their marine ancestors. They have adopted decidedly terrestrial habits: they retreat into burrows when the beach is covered by water; they emerge to feed, in air, on the sand surface when the tide is out; they even take up oxygen from the air rather than from water using gills (i.e., they have aerial gas exchange). These crabs well and truly do not like getting wet, sitting out the high tide in a trapped air pocket inside their burrows. Terrestrial animals have lungs to take up oxygen and get rid of carbon dioxide. The sand bubbler crabs have developed a somewhat more unorthodox solution for gas exchange: parts of their legs are slightly flattened out and covered with a thin membrane. Zoologists have falsely thought that these organs are used for hearing and hence named them 'tympanum', a reference to the eardrums ('tympanic membrane') of vertebrates, including us humans [68]. The crabs use these membranes for aerial gas exchange, and they do not want to hear another word about the ears on their legs. Some beach crabs carry their lungs on their legs—a breath of fresh air in animal evolution.

(8.) *Vegan Beach Flies Wearing Stilettos Feed by Step Dancing.*

The top few centimetres of beach sands contain enormous numbers of minute algae, a good food source. However, these minute, one-celled algae are smaller than the sand grains; they also tend to stick to the sand grains. Being sticky and small makes it devilishly difficult to get to the food morsels (algae) without ingesting copious volumes of sand. Sand is bad because it fills up the gut with nutritionally useless dead volume. Sand is bad because it is heavy ballast (a big problem for a flying insect). So how does a flying beach animal wanting to exploit this rich food source winnow the sticky grain (algae) from the chaff (sand)? Engineers would suggest a four-step process: (i) loosen the algae from the sand grains they are attached to; (ii) lift the dislodged algae into a watery mixture of algae and sand; (iii) let the heavier sand grains settle out to the bottom; and (iv) slurp up the delicious algae soup from the top (hopefully with few gritty bits). A beach fly (yes, a humble fly; *Lipochaeta slossonae*) has found a solution to make this ‘floatation separation’ work on ocean beaches: the flies tap quickly with their feet on the moist sand; this loosens the algae from the grains. The fly’s tapping step dance also creates a thin layer of water in which the dislodged algae float to the top whilst the sand grains remain at the bottom. (One can easily mimic this by tapping gently and quickly on wet sand; after a few seconds, the top layers of sand should fluidise). All that remains for the fly to do is to slurp the delicious algal soup—Bon appetite. If step dancing to create an algal soup were not awesomely amazing enough, the flies have another trick up their sleeve: The flies are covered in a coat of velvet hair. To avoid getting their splendid ‘fur coat’ wet, the flies stand on ‘high heels’, formed by strong spines pointing downwards from the tip of their legs—an uncanny resemblance to stilettos [69]. Beach flies in Louboutin stilettos: When high fashion meets high achievement in foraging innovation?

(9.) *Surfing Beach Snails Are Über-Cool.*

Dead animals of all types and sizes wash up on the world’s sandy beaches. The influx of high-quality animal protein, delivered in discrete packages that do not need to be chased, hunted down, and killed (all very dangerous activities), is a hugely attractive event for animal consumers on sandy shores. Not surprising, sandy beaches contain many species of scavengers, all wanting to feed on stranded carcasses. It follows that detecting a carcass fall, and getting to it before others do, are two traits at a premium for any beach scavengers worth its salt. Snails (*Bullia digitalis*) on South African beaches have mastered both. They have a highly acute sense of smell, detecting the tiniest amount of chemicals leaching from an animal carcasses. So far, so good—rapid detection is solved. However, snails are hardly known for speed, a massive handicap for a scavenger that needs to access a carcass swiftly. The snail’s solution to quickly reaching a dead body washed up on a beach is pure genius: SURF! Yes, the snails evolved a large foot that can be rapidly inflated to function as a ‘sail/board’ in the low waves bores (called ‘swash’) running up and down a beach. The snails use their foot (aka ‘surf board’) to ride the swash up the beach expertly, thereby carrying it towards the delicious dead animal of choice. Remarkably, the snails appear to have control over direction and distance. They surf at an angle to the flow of the swash, and, like a sailing ship, they tack in a zigzag trajectory towards the food item. After a few swash rides, the surfing snails typically reach their food—voila [70–72]. PS—Four species of antson a Venezuelan beach have entered this evolutionary ‘invertebrate surfing carnival’, with some adroit individuals able to ride small foam crests [73]; at this stage it remains unknown whether the cool South African surfer snails now have ants in their boardshorts. Surfing snails on sandy beaches are so über-cool that they risk frostbite.

(10.) *Incisive Decisions in Evolution and the Grant Meetings of the Mammals: It All Happens on Coasts.*

Shorelines are full of evolutionary drama. They are the theatres that staged major radiations in animal life and tested new adaptive solutions when animal clades conquered new realms. The role of shorelines as evolutionary interface regions is most spectacularly

illustrated by the appearance of terrestrial mammals from their aquatic ancestors. By contrast, the ‘reverse engineering’ of whales leaving the beach again to return to a marine mode of life also featured shores as transitional environments. Mammals (including us) mostly sport a rich potpourri of adaptations to terrestrial life (e.g., burrowing, galloping, hopping, bipedal walking, tree climbing, gliding, hair, lungs, etc.). However, not all mammals fancied this new life on dry land, returning to the aquatic milieu of their vertebrate ancestors. Whales and dolphins did this with such aplomb that they now outperform some of the fishes and sharks (the unadventurous clade of slimy, scaly, water-loving beasts) when it comes to swimming, diving, and hunting [74]. For other marine mammals, the connection to marine shores remains strong to this day: take, for example, seals that use beaches as haul-out sites to court, breed and give birth. Terrestrial mammals ‘spill over’ from terrestrial habitats to patrol marine strandlines for animal carcasses to scavenge and to hunt. The planet’s ocean beaches are foraging sites for a veritable zoo of carnivore species, including wolves, bears, lions, jaguars, foxes, leopards, dingos, Tasmania devils, hyenas, otters, genets, weasels, badgers and many others [75].

No matter what perspective (land-to-sea vs. sea-to-land) or time window (ancient vs. modern) one adopts, coasts are the biosphere’s unique interface that connects the sea and land across the aeons (Figure 2). Fundamentally, coasts are edges. Edges, where the ancient meets the modern. Edges, where iconic animal clades trialed aquatic versus terrestrial modes of life (and vice versa) in vertebrate evolution. Edges, where large and iconic predators roam the shores to scavenge and hunt. Edges, where our spirits are lifted when seeing these carnivores. Coasts are edges that do it all.



Figure 2. ‘Parrots on the Beach’. Coastal ecosystems are fascinating places where new ‘discoveries’ always await. We have recently encountered large flocks of parrots feeding on masses of tumbleweed seeds rolling from the dunes onto the beach in Eastern Australia; this is an ‘exciting discovery’ because it runs counter to a widely-held view about how food webs on beaches are thought to function. A paradigm about the function of food webs on wave-exposed ocean shores builds mainly on the supply of organic matter that is produced at sea and subsequently flows shoreward to ‘subsidise’ animal consumers on sandy beaches. By contrast, primary production on the beach itself is considered relatively minor. Flows of organic matter from the dunes to the beach are also typically small compared with the substantial onshore flows of marine production in the form of detached algae (kelp), seagrass, phytoplankton and animal carcasses. Thus, conventional wisdom postulates that the prevailing direction in which translocated organic matter flows between habitats is typically from the sea to the beach: almost all organic material supporting beach food webs is thought to come from the ocean being washed up on beaches where it underpins the local food webs. Well, well, well: Here, we have terrestrial primary production flowing, en masse, from the dunes to the beach—the opposite direction to conventional wisdom. Notes: The Plants: The tumbleweeds are formed by the rolling spinifex grass (*Spinifex sericeus*; other common names: hairy spinifex, beach spinifex, coastal spinifex). The grass is a widespread pioneer plant on the ocean-facing foredunes of Australia, New Zealand, New Caledonia and Tonga. At maturity, the female inflorescence detaches as a globose (up to 20 cm in diameter) seed head, which becomes a tumbleweed; the tumbleweeds can occur en masse on beaches when large numbers of seedheads mature and detach at the same time. The Birds: Little Corella (*Cacatua sanguinea*) are widespread throughout Australia. They feed in large, noisy flocks, mainly on the ground, the most common food items being grains and grass seeds (as in this observation). ‘Fun Fact’: Little Corellas like to play, an unusual activity amongst birds. They can slide down the roofs of wheat silos, tumbling off the edge before flying back to the top for another slide. Little Corellas have also been observed perched on the blades of windmills, spinning round and round, falling off and then regaining a precarious grip on the blades (<https://birdlife.org.au/bird-profile/little-corella>; accessed 27 October 2022).

4. Human Stressors Impacting Coastal Systems

4.1. Retreating Sandy Shorelines

No perspective on coastlines can be complete without explicit recognition of the main anthropogenic stressors that impact shorelines worldwide. Arguably, the main topic in the limelight illuminating coastal environmental change is erosion, particularly the vulnerability of sandy shorelines. Sandy beaches, and other sedimentary shorelines, have irreplaceable values that encompass rich social, economic-, cultural-, and conservation facets [76]. However, perhaps the most highly prized ecosystem service that sandy beaches provide to human societies is safeguarding assets and lives from the tempestuous forces of nature, especially the protection afforded by dunes against destructive flooding during storms (Table 1).

Humans' prime perspective on sandy beaches is often their 'buffering capacity' to counteract coastal hazards. In many cases, such 'storm protection' is the sine qua non for human settlements to exist along ocean-exposed coastlines. Adequate sediment supply is necessary for beaches and dunes to function as buffers. Storm protection also depends on beach width, the volume and elevation of dunes, the capacity of shorelines to move landwards when sea levels rise ('accommodation space'), and the ability of dunes to rebuild after pulsed erosion events. Human interference with natural processes has compromised all of these, making 'shoreline retreat' a cardinal issue faced by numerous communities living along sandy shorelines [8].

Erosion of beaches and cliffs is not a recent phenomenon; the scientific literature contains accounts of shoreline change dating back to the second half of the 19th century (Table 1). However, what is remarkable is how the spatial ambit of our analyses has expanded from local phenomena to a truly global reach [8]. We also have moved from being almost exclusively focused on storms to documenting and predicting the impacts of sea-level rise caused by climate change [9].

Coastal retreat, or advance, can also be gauged with direct measurements of coastline position, using evidence from geological methods like coring, age control, sedimentological analyses [77]. Insights from past trajectories can be valuable to better predict how coasts might react in the future, including the fate of sandy shorelines [78].

Table 1. A precis of shoreline erosion reported in the peer-reviewed literature over more than a century. Listed studies are examples, drawn from a much wider literature, selected for three main purposes: (a) to sketch the timeline of observations on shoreline retreat, (b) to outline the evolution of identified driving forces (transitioning from local/regional factors to sea level rise associated with climate change), and (c) to illustrate the expansion of the spatial ambit, moving from local scales to global impacts.

Year	Location	Main Observations	Reference
1882	England (Hampshire Coast)	- Cliff erosion - <i>'The degradation of the cliffs to the westward has been very great, and they are much serrated and water-worn, with frequent slips in the upper strata of sand and gravel on a clay base, and in the neighbourhood of Hordle huge masses of fallen cliff alternate with hollow chines.</i> - <i>'At Barton also the loss is great, averaging over certain periods one yard per annum, and the whole frontage of Christchurch Bay is similarly affected'.</i>	[79]
1892	England (Devonshire Coast)	- Episodic (pulsed) nature of beach erosion, alternating between losses during storms and gradual rebuilding during calms. <i>"Sea-waves, tidal-currents, and river-currents can be observed, and their effects recorded, but it is the occasional, irregular, and sometimes powerful wind-raised current, prevalent during storms, which performs such erratic feats, and deludes the unvarying observer. For instance, a beach may resist the sea for years, yet in a few hours it may be stripped bare to the solid rock"</i> .	[80]
1899	Netherlands	- Decadal (1846 to 1894) record of landward movement of the shoreline at a rate of ~ 1 m a year. - <i>'As a general result, the measurements show that during the last half-century, on the Dutch coast, the sea has been encroaching on the coast. The low water line has crept landward, and the beach has become more steep. There has also been a wasting away of the foot of the sand dunes'.</i>	[81]
1983	Australia (New South Wales)	- Long term (1895–1980) record of shoreline position in response to climatic variability at the scale of ocean basins. - <i>average high-tide wave run-up position measured accurate to ± 2.5 m from oblique and vertical photographs, changes could be linked to regional sea-level variation and a globally significant climatic variable, the Southern Oscillation (SO).</i>	[82]
1997	USA (Hawaii)	- Shoreline armouring can result in increased rates of beach loss if hard coastal defence structures concentrate wave energy and/or block sand movement from dunes to the beach. - <i>"The authors identify coastal armouring structures, built to protect shoreline properties from erosion, as the culprits. The trouble is that armouring concentrates erosional forces on the beach directly in front, which, moreover, also loses the replenishment of sand stores from those locked into shoreline land"</i> .	[83]
2016	England (East Sussex)	- Millennial records of cliff erosion and beach width. - Beaches fronting cliffs shield cliffs from storm-induced erosion. - <i>'... retreat rates of chalk cliffs that were relatively slow ($2\text{--}6\text{ cm}\cdot\text{y}^{-1}$) until a few hundred years ago. Historical observations reveal that retreat rates have subsequently accelerated by an order of magnitude ($22\text{--}32\text{ cm}\cdot\text{y}^{-1}$)'.</i> - <i>'We suggest that acceleration is the result of thinning of cliff-front beaches, exacerbated by regional storminess and anthropogenic modification of the coast'.</i>	[84]
2018	Global	- Decadal (1984–2016) record of shoreline change for sandy beaches worldwide. - 24% of the world's sandy beaches persistently eroding at a rate exceeding 0.5 m year^{-1}. - 16% of sandy beaches are experiencing erosion rates exceeding 1 m year^{-1}. - 37% of protected sandy shorelines are eroding at a rate larger than 0.5 m year^{-1}.	[8]
2020	Global	- <i>'13.6–15.2% (36,097–40,511 km) of the world's sandy beaches could face severe erosion by 2050, a number rising to 35.7–49.5% (95,061–131,745 km) by the end of the century'.</i> - <i>'By 2100 Australia is predicted to potentially experience severe erosion along 11,426 km of sandy beach coastline'.</i> - <i>'Ambient trends in shoreline dynamics, combined with coastal recession driven by sea level rise, could result in the near extinction of almost half of the world's sandy beaches by the end of the century'.</i> - <i>'A substantial proportion of the threatened sandy shorelines are in densely populated areas, underlining the need for the design and implementation of effective adaptive measures'.</i>	[9]

Predicting the exact trajectories and rates of local and regional shoreline change is challenging. This is not surprising, given the many factors at play such as sediment supply, armouring structures, climatic events at decadal scales, rare mega-storms [17,82]. It does, however, stand to reason that the eye-watering observations and predictions of potential beach loss [8,9] are a call to arms to combat climate change with élan and do so at scale.

4.2. Pollutants That Connect Coastal Systems

Shoreline erosion is, of course, not the only game in ‘anthropogenic stressor town’. The range of environmental harm caused by humans to coastal systems and organisms is a depressingly vast and multifarious one. It is interesting to note that questions about the presence, distribution and biological effects of chemical pollutants and nutrients (e.g., N + P [85] in beach systems have only been asked since the late 60s and early 70s [86–88]. Examining pollution questions is critically important from a human-health perspective, especially given the intense recreational use of beaches [89].

Pollutants can also provide insights about connectivity amongst different ecosystems in the coastal zone. In settings where rainfall occurs in distinct pulses in coastal watersheds, estuaries can export prominent turbidity plumes to nearshore waters during and after intense rainfall bouts [90]. These plumes translocate nutrients, organic matter, and pollutants from the catchments to marine waters (a form of ‘spatial subsidy’). Marine organisms can incorporate this translocated matter, illustrated by enhanced plankton growth and the presence of isotopic signatures in marine fisheries species that are typical for estuarine organic matter [91–93]. Human sewage is often isotopically distinct from other forms of nitrogen. When sewage is discharged to estuaries, stable nitrogen isotopes can track this distinctive sewage-N signature in the receiving waters and the tissues of fish and other organisms exposed to sewage-N [93–95]. Isotopes characteristic of estuarine sewage can also function as a tracer to test whether estuaries are functionally linked with ocean beaches. For example, in Eastern Australia such ‘land-ocean coupling’ was tested by examining stable N-isotopes in wedge clams collected from ocean beaches near and far an estuarine inlet. Clams near the inlet, exposed to estuarine plumes, carried a distinct estuarine sewage signal. By contrast, clams remote from an estuary had a typical marine isotope signature, demonstrating the transfer of the estuarine matter to marine consumers on ocean beaches [94].

4.3. Human Impacts on Sandy Shores: A Diverse Collection of Impact Types

Several syntheses have summarised the main pressures and their ecological impacts on ocean beaches [76,95–98]. It is beyond the scope of this perspective to give a detailed account of the full range of anthropogenic effects. Still, typically, the existing published summaries of human impacts in the coastal zone focus on biological responses to about ten commonly encountered types of human stressors.

1. Armouring (e.g., seawalls, breakwaters, groynes) [7,20,99–105]
2. Nourishment (e.g., sand additions, re-profiling) [106–115]
3. Fisheries (e.g., recreational, artisanal, clams, bait) [32–35,116–128]
4. Off-road Vehicle Traffic (e.g., off-road traffic, recreation) [95,129–146]
5. Grooming (e.g., removal/cleaning of natural wrack deposits) [147–152]
6. Trampling (e.g., crushing of plants and animals) [6,89,153–162]
7. Water Quality & Toxicants (e.g., nutrients, microbial, human health, chemical pollutants) [58,93,94,163–172]
8. ‘Urbanisation’/Multiple Human Uses (e.g., habitat loss) [11–13,29,76,96,97,173–194]
9. Invasive Species & Feral and Domestic Carnivores (e.g., foxes, fire ants) [75,195–199]
10. Anthropogenic Debris (e.g., litter, rubbish, plastics, microplastics) [200–208]

In contrast to these well-covered themes, there is little work on light and sound pollution, groundwater contamination, and algal blooms in high-energy surf zones [209]. Many studies have covered multiple pressures related to the increasing urbanisation and concomitant human footprint in the coastal zone [6]. The existence of several urban stressors acting at the same time in the same place makes it devilishly difficult to attribute observed biological changes to distinct human stressors correctly; unravelling the specific effects of specific factors, notionally viewed to work in concert, presents as an inviting intellectual challenge to coastal ecologists.

One theme that has not been covered adequately in the literature reviewing impacts on sandy beaches is the recent explosion of papers on anthropogenic debris, especially plastic that washes up on all sandy shores, even on the most remote beaches [210]. Massive changes in the way and number of people that use sandy beaches during the COVID pandemic resulted in modified ecological patterns and processes, some positive and some negative [211,212].

Last but not least, it requires little extra emphasis that every coastal structure and process be it a geo-morphological, hydraulic, meteorological, socio-economic, or ecological one, is altered by climate change [213]. Indubitably, climate change and humankind's response to it in the Anthropocene is *primus inter pares* as the single most powerful global force that dictates whether and how coasts can accommodate humans in the coming decades.

5. Principles to Guide Environmental Solutions

Attempting to write about 'solutions' for coastal problems in a few (or many) paragraphs is, depending on one's perspective, ambitious or naïve. Gallantly (and perhaps naively), here we do just that, trying to sketch the essence of an, admittedly, idiosyncratic collection of three principles posited in equal measures for reflection and to stimulate debate.

5.1. Protect Remaining Natural Land

Climate change causes sea levels to rise, and it alters storm regimes [214,215]. Rising sea levels and storms force coastlines to move landwards, threatening settlements ranging in size from holiday cottages to megacities [17]. Shoreline retreat under rising seas can be accommodated on sparsely populated coastlines. However, much of our coast is now urban, containing little or no accommodation space for shorelines on the move. Loss of coastal land not only severely limits our options to respond to climate change; it also means a loss of coastal habitats and a loss of coastal biodiversity. Consequently, constraining the human footprint in the coastal strip places a massive premium on protecting all remaining natural areas. This interplay between climate change and habitat loss constitutes the very pointy end of how coastal societies make decisions about the types and longevity of environments they want to inhabit at the edge of the sea.

5.2. Working with Nature to Enhance the Resilience of Coasts

Society will defend coastal settlements at the edge of the sea and, in many instances, has little alternative but to seek to enhance the *resilience* of coastal. Defining 'resilience' is not a trivial task [216,217]. but perspectives that focus on the continuity of essential processes and services delivered by coastal systems appear a sensible way forward (e.g., the 'capacity of the socioeconomic and natural systems in the coastal environment to cope with disturbances by adapting whilst maintaining their essential functions' [218]. Affluent coastal societies will likely have to invest heavily in engineered solutions to combat receding shorelines. This strategy has a long tradition and can be spectacularly successful if done well [8]. There are many examples where poorly planned or executed 'coastal defence' structures did precisely the opposite—accelerate erosion [219]. Whenever and wherever civil engineering is the method of prime choice to strengthen protection against coastal hazards, adopting the ethos of 'building with nature' may seem a sensible strategy to incorporate more ecological thinking into public works [220,221]. All else being equal, it stands to reason that strengthening the resilience of coasts requires in many cases to find a compromise between ecology, economy, social and cultural aspirations and technical feasibility.

5.3. Common Goals for a Common Good

As coastal citizens, we are willing to invest vast sums of energy and money into saving our shores when faced with threats that insult our sense of justice and stir our souls. Our collective actions to clean coastlines that oil spills have spoiled is a brilliant example that we

do care about coastal environments. The fact that millions are spent to try and remedy the harm caused by oil coming ashore signifies that society deeply values ‘clean’ shorelines and the health of plants and animals they support [222]. Yet, there is a veritable litany of failures in how the civil service manages coastlines and loses sight of these values. Many papers lament that the quagmires of bureaucracy swallow up citizens’ goodwill. The quicksands of government also trap the civil service itself. The unholy alliance of quagmires and quicksands produces disjointed attempts to repair shorelines using engineered structures that can create new ecological problems and lack community buy-in.

There is nothing new about the byzantine shortcomings of governments and governance in coastal management [223]. It is also not fruitful to be dramatically evangelical about the need to drain the swamps of bureaucracy—a task that is best added to the repertoire of Sisyphus. However, what many coastal communities and citizens have are gloriously uplifting and fierce spirits—spirits that value the narrow tongues of shifting sands that are their fragile home at the edge of a tempestuous ocean. These spirits are the very fabric to tailor fresh and inclusive models that will enhance coastal resilience. They are the foul-weather gear to embrace nature-informed engineering. They are the fierce defiance driving protection of habitats and biodiversity. We can embolden this fierceness by creating fresh and trusted knowledge built on solid science that needs to rise to these challenges armed with a fierceness and freshness of its own.

Author Contributions: Conceptualization, T.A.S., B.M. and M.A.d.S.; writing—original draft preparation, T.A.S., B.M. and M.A.d.S.; writing—review and editing, T.A.S., B.M. and M.A.d.S. All authors have read and agreed to the published version of the manuscript.

Funding: No specific, targeted, funding applies to this paper.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data are already in the public domain, in the form of published papers.

Acknowledgments: The authors thank their institutions/employers for granting the academic freedom to explore coasts.

Conflicts of Interest: The authors declare no conflict of interest.

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